THE REEFS OF TUTUILA, SAMOA, IN THEIR RELATION TO CORAL REEF THEORIES.

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The Island of Tutuila, American Samoa, is purely volcanic, no elevated limestones having been observed upon it. As has been shown by Daly the exposed volcanic rock is in most places weathered to its ultimate degree, but this does not apply to the region of the southwestern shore between Tafuna and Sail Rock, where a lava flow occurred in times so recent that its surface still shows a ropy structure, while sharp-edged cracks and numerous lava caverns remain open quite as they were at the time of their formation.

The Island is strongly cliffed by the sea, some of these cliffs as at Round Bluff being fully 300 feet high. After forming these cliffs the sea level sank so as to expose a platform of hard volcanic rock which projects from 50 to 250 feet seaward from the foot of the basaltic promontories. The recent lava flow between Tafuna and Sail Rock overwhelmed this platform but elsewhere practically every promontory of the Island shows this old emerged shore-shelf, and remnants of it appear in numerous places lying off shore within the bays, such as in Afonu, Vatia, Fagasa, Leone and Pago Pago harbors, and especially along the south coast between Breaker Point and Fagaitua Bay. It is also found around the off-lying island of Aunuu southeast of Tutuila.

The bays of Tutuila are in regions of fragmentary material and are flanked by ridges of harder rock. Thus the emerged shore platform has resisted erosion where it is composed of basalt as at the spur ends, but has largely disappeared within the harbors where the rocks are generally soft.

A similarly elevated shore-shelf of volcanic rock is found around the islands of the Manua Group, Ofu, Oloosega and Tau, and also at Rose Atoll where it is of hard dolomitized limestone bearing corals. As this shore bench is identical in elevation in these separated islands of differing ages and histories, Daly is justified in the inference that it indicates a relatively recent subsidence of sea level rather than an elevation of the Islands. Indeed a relatively recent emergence of about 8 feet above high tide level is shown by the Atolls of the Paumotos, and Ellis Groups, as well as by the islands in Torres Straits, and the southern shore of Papua in the region of Port Moresby. It appears also in the Florida Keys and the Bahamas, and A. Agassiz, 1903, Proc. Royal Soc. London, Vol. 71, p. 413, says that "Throughout the Pacific, the Indian Ocean, and the West Indies the most positive evidence exists of a moderate

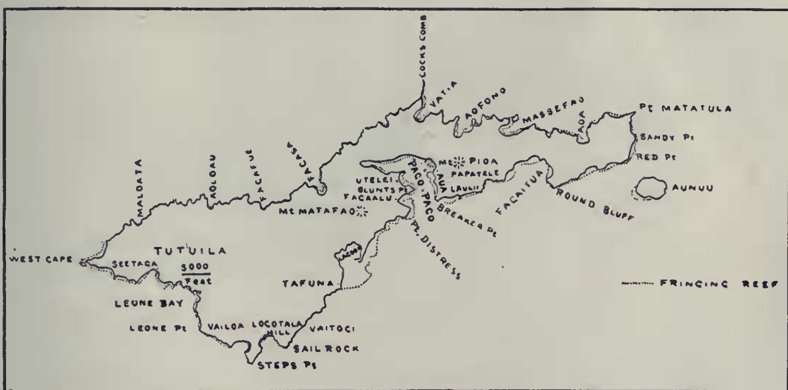

Fig. 1. Tutuila, American Samoa. Showing fringing reef now growing around the Island in places where the submarine slopes are not too steep.

recent elevation of the coal reefs." Indeed Daly records a moderate recent emergence of the land along many thousand miles of coast line not only in the tropical, but also in colder regions.

In the volcanic islands of American Samoa there are no traces of elevated coral reefs, or limestones except small fragments thrown up by volcanic action and imbedded in ejected volcanic ash as at Aunuu, or in a crater rim south of Logatala Hill, Tutuila, or each of Faleasau Village on Tau Island.

No corals or limestones are found imbedded in or resting upon the emerged shore bench around Tutuila; nor were any ancient corals tossed up by sto ms on the beaches of the inner parts of the ancient harbors although such would have been the case were coral reefs growing along the shores at the time when this emerged bench was at sea level. Moreover, in places as at Fagatoga this old shore bench was partially covered by talus sliding down from the cliffs, but upon digging this talus away no elevated corals or limestones were found. We are thus forced to conclude that during the time when the sea was at its highest level and cut the now emerged shore-bench, there were no coral reefs growing around Tutuila.

The fringing reef which is now growing outward from the shores around Tutuila, in places where the slope is not too steep, is of modern origin. It is 300 to 1,000 feet wide in places where the underlying volcanic slope is gentle, and is narrow, or absent in places where the submarine slopes are steep as off the seaward ends of the basaltic promontories. Thus the reefs now growing outward over the gentle, wave-worn slopes of the drowned valleys are wider than those off the cliffed promontories at the mouths of the harbors, and everywhere the width of the reef is a factor of the steepness of its underlying volcanic substratum.

The fact that narrow reefs are found on steep submarine slopes and wide ones on gentle slopes was pointed out by Darwin in "Naturalist's Voyage around the World," 1873, p. 472; also A. Agassiz, 1903, *Proc. Royal Soc.*, Vol. 71, p. 414, says that the absence of coral reefs in the Marquesas Islands is due to the steepness of their slopes.

Tutuila is very ancient according to Daly, who has made a survey of its lithology (Year Book of the Carnegie Institution No. 18, 1919). Indeed it shows clear evidence of considerable subsidence, the harbors of its northern coast such as Fagasa, Vatia, Afono, Massefau and Aoa being typical drowned valleys, while Pago Pago Harbor, according to Daly, shows characteristics of a drowned valley but has had a complex history.

W. M. Davis (1918, *Bulletin U. S. Geological Survey,* p. 523) observed that the data for the unpublished Hydrographic Office Chart of Tutuila "reveals the existence of a submerged platform from one to three miles in width and from 30 to 50 or more fathoms in depth," and also that "the outer part of the platform is usually somewhat shallower than at half distance off shore as if a poorly developed barrier reef enclosed it."

I find upon contouring this chart (Fig. 2) that it indicates that Tutuila was once surrounded by a wide barrier reef and that also a well-developed fringing reef extended out from the shore and fused in many places with the barrier reef, obliterating the lagoon between them. This fusion of the two reefs was well seen along the north coast between Vatia and Maloata, but it occurred also on the south coast off Cocoanut Point. The lagoon between the barrier and the fringing reef of the southern coast of Tutuila was in many places at least 20 fathoms deep; but along the north coast between Vatia and West Cape it was shallower and was thus largely

FIG. 2. The dotted areas show the ancient barrier and fringing reefs which once surrounded Tutuila but are not submerged about 190 feet below sea level.

obliterated by the fusion of the fringing reef with the barrier, for the lagoon between these reefs was in most places not more than 2 to 4 fathoms in depth.

As was suggested by Daly this greater depth of the lagoon along the southeastern shore indicates that there was an actual subsidence of the island itself, the southeastern coast sinking more than the northern shore: At any rate these ancient barrier and fringing reefs are now submerged to a depth of about 30 fathoms. As reef-building corals can grow only sparingly at depths greater than about 18 to 20 fathoms, these ancient reefs are drowned and in most places are probably not at present growing upward. In many parts of the Taema and Nafanua Banks, however, the depth is now less than 18 fathoms and modern corals are growing in patches in such places, but the coral heads are small, and the spaces between them usually wide. In places where the depth is as great as 8.5 fathoms, corals such as *Acropora arcuata* are not more than one foot wide, whereas this species attains a diameter of three or four feet in water not more than 2 to 4 fathoms in depth.

These ancient reefs of Tutuila may have been drowned too suddenly to permit coral growth to maintain them at the surface, or as seems more probable, conditions may for long periods of time have been unfavorable for corals, thus permitting a gradual subsidence or a slow rise of sea level to effectively drown the reefs under a depth too great to permit the renewal of coral growth when conditions became otherwise favorable.

Moreover, we know from observation made at Tortugas, and from those of Wood Jones at Cocos Keeling that a coral reef once killed may not renew itself in half a century. At Tortugas the *Acropora muricata,* which constituted wide areas of shallow reef, were killed by the "dark water" of October, 1878, and even to-day (1920) it is a rare coral over the flats where once it was the dominant species; and very similar conditions are described by Wood Jones in his "Coral and Atolls" for the lagoon of Cocos Keeling.

Moreover, there are many places along the shore of Tutuila as at Vatia, or near Fagaalu, where corals which once grew upon the reef flat were torn loose and driven ashore by an unrecorded hurricane which must have occurred more than fifty years ago, yet these reefs have not recovered and are quite smooth and devoid of coral heads.

It appears that a reef once established can readily maintain itself, but once it be destroyed many years may elapse before corals can again attain a foothold. Thus on steep slopes if corals which die or are broken off roll down into water too deep for coral growth, a reef may be greatly hindered in establishing itself, and thus one may have the condition seen in the Marquesas Islands where numerous scattered coral heads are found growing upon the submarine volcanic slopes, but they have not yet succeeded in establishing reefs. Coral reefs can readily form upon relatively flat submerged or subsided platforms but steep slopes are unfavorable for their initiation and maintenance.

A study of the submarine slopes of the fringing reefs of Tutuila was made by casting out an anchor upon the seaward edge of the reef, and then steaming seaward in the launch keeping the anchor-line taut and making soundings at distances of 25, 50, 75, 100 feet, etc., from the edge of the reef. This enabled us to determine the slopes as shown in Fig. 3, which represents the conditions seen in various parts of Pago Pago Harbor. The vertical and horizontal scales are the same in these diagrams. We see that the growing edge of the reef usually overhangs at sea level, due to the dense clustering of the rapidly growing *Acropora leptocyathus* in this region, and to the fact that when they die these corals are maintained in place by the overgrowth of lithothamnion. Under this

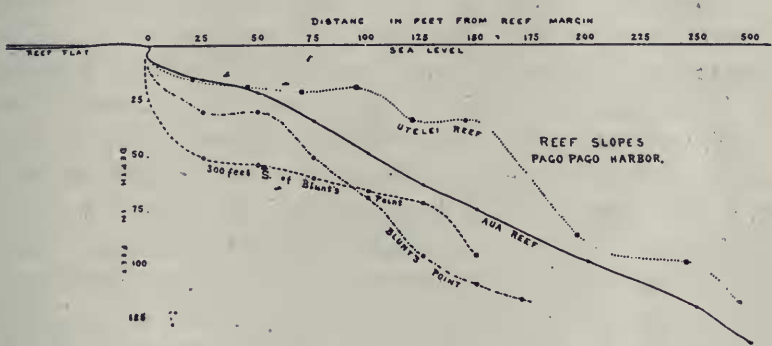

FIG. 3. Submarine slopes off the seaward edges of reef flats of Tutuila.

overhanging edge there is a submarine precipice of usually 5 to 25 feet in depth, beyond which there is a narrow region which is relatively flat, and where corals grow vigorously but cannot reach the surface, due to the surges of the breakers which fracture their stems in time of storm. Beyond this lies the seaward slope composed chiefly of loose dead and alive coral fragments, the talus of the reef, which extends downward at an average angle of about 25° to 30°, thus being somewhat steeper than the average subaërial slopes of volcanic islands. As this talus sets itself at an angle of repose of 25° to 30° it would seem that a slope steeper than this would be unfavorable for the starting of a coral reef, for whenever a coral died or was broken off it would roll down the slope; and new corals are slow to gain a foothold except in the immediate vicinity of densely clustered living coral heads.

The inner ends of the bays of Tutuila were partially filled in by delta-plains when the sea stood higher than at present, but these have shared in the general emergence of about eight feet, and thus their swamps were drained, only a few small recent mangrove swamps being now found as at Massefau, Leone, Vatia, and several places along the shore of Pago Pago Harbor, as at Aua and Utelei.

During the past fifty years or more, no severe hurricanes have passed over Tutuila, but there is abundant geologic evidence of their presence in recent times. Thus the reef flats near the mouth of Pago Pago Harbor bear many large erratic coral masses which have been torn off from the edges and tossed up upon the platform of the reef. One of these fragments at the edge of the reef off the southern end of Aua village in Pago Pago Harbor is so large that the Harbor chart records it as "Coral Block 3 ft." Also at Vatia, Laulii, and many other places, there are masses of recently broken coral driven up 10 feet above high tide level and now lying covered with moss under the dense shade of the largest forest trees which have grown over them since the hurricane tossed them up as wreckage upon the desolated shore. In ancient times we see that Tutuila was partially surrounded by a barrier reef which had grown upward along the seaward edges of a platform of marine erosion which had become submerged by the subsidence of the island itself. Fringing reefs were at the same time growing outward from the shore and in many places, especially along the northern coast had fused with the barrier reef. Then due to a rising of the sea level combined with continued subsidence of the land mass these old reefs were drowned, and for a long period we find the island unprotected by any reefs while the sea cliffed the shores not only at the promontories but well within the drowned valleys. Finally the sea level sank about 20 feet below its highest level and after this, in modern times, a fringing reef began to grow outward from the shores and has now attained a maximum width of not over 1,000 feet. Also in modern times coral patches began to grow upward upon the Taema and Nafanua Banks in places which were probably islands well above sea level at the time when the ancient barrier reef was formed and were thus covered with less than 20 fathoms of water when reefs began again to grow around Tutuila. These reef patches have now approached to within 6 or 7 fathoms of the surface in a few places. The average width of the old drowned barrier reef was quite 2,500 feet, and thus, if the growth rate of corals has remained unchanged, it probably existed around the island for a longer time than has sufficed to form the present fringing reefs of Tutuila. The ancient drowned reefs around Tutuila indicate that fringing reefs did not become transformed into barrier reefs in the manner postulated in Darwin's Theory but contemporary fringing reefs grew outward and fused with the barriers which were formed *in situ* along the seaward edges of the submerged platform.

In formulating his subsidence theory of the supposed sequence of fringing reefs, barrier reefs and atolls, Darwin failed to consider certain factors which are now well recognized. For example, his theory, as he advanced it, presupposes subsidence of the land rather than an elevation of sea level, nor did he consider the effects of cliffing of shores, the making of platforms of marine planation, or the drowning of valleys upon which Davis lays constant emphasis. To his mind coral growth was probably continuous throughout long periods. Just what relations if any existed between periods of glaciation and periods of poor development of coral reefs is as yet obscure even in the Atlantic. Thus Vaughan (1919, *U. S. National Museum Bulletin* No. 103, p. 226, etc.; also, 1918, *Bull. Geol. Soc. America,* Vol. 29, p. 629) shows that in the West Indian-Florida region there was a maximum development of coral reefs in the middle Oligocene, which was a period of maximal submergence in this region, and at which time the Atlantic and Pacific were connected. In the Miocene and Pliocene only poor reefs were developed, no Pliocene reefs being known from the West Indian Islands. Later in Pleistocene and recent times there has been an extensive growth of coral reefs. According to Vaughan in the Oligocene fifteen genera of corals found at present only in the Pacific and Indian region were growing in the West Indies. Such genera were *Pocillopora, Pavona, Favites, Goniopora, Goniastrea, Galaxea, Stylophora,* and *Alveopora,* and seven others; but they disappeared from the West Indian reefs before Pliocene times (Vaughan, T. W., 1917, *U. S. Geological Survey, Professional Papers,* 98 T, pp. 355–376). According to Daly, coral growth was retarded during periods of *lowered* sea level and coincide with periods of glaciation when water was taken out of the oceans to constitute the continental ice sheets; but in Tutuila we have evidence that at the time of *highest* ocean level coral reefs did not grow around the island.

However, Ulrich (1920, *Journal Washington Acad. Sci.,* Vol. 10, pp. 57–78) states that the pressure of an ice sheet may depress the level of the interior of a continent, and this movement tends to be compensated by an elevation in the strand-line. Thus the rise in the continental shelf and of the coastal waters may more than compensate for the water taken out of the ocean to form the ice sheet, and there may even be a rise of sea level at a time when continental land areas are glaciated.

Unfortunately we as yet know practically nothing of the geologic ages of the ancient elevated reefs of the Pacific and have as yet no means for ascertaining their relation in time to those of the tropical Atlantic.

Guppy (1890, *Trans. Victoria Institute,* Vol. 23, p. 60) held the opinion that the corals of the Great Barrier reef were growing on the seaward edges of a submarine plateau, and Andrews (1902, *Proc. Linnean Soc. New South Wales,* Part 2, pp. 145–185) shows that the submerged continental shelf along the coast of Queensland extends southward into the temperate regions, and that the more or less detached coral patches which form the Great Barrier Reef could not have formed the platform but merely grew here and there along its seaward edge after the platform was submerged, and conditions became favorable for coral growth. Indeed as I observed in 1913 the Barrier Reef ceases at the Murray Islands, while the platform upon which it is growing extends northward to the shores of New Guinea, but corals cannot grow in this region due to the mud discharged from the Fly and other great rivers of Papua. Thus this platform extends both northward and southward beyond the limits of coral reef growth. Alexander Agassiz held the opinion that the modern reefs of the Pacific were growing unconformally upon the ancient limestone platforms and ledges.

Vaughan (1914, *Journal Washington Acad. Sci.*, Vol. 4, pp. 26–34) showed that the platform upon the seaward edges of which the Florida reef is now growing, extends northward into a region too cold for coral growth. Moreover, the disconnected coral patches which rim the seaward edges of the Great Bahama Bank are many of them growing not at the extreme edge of the bank but at an appreciable distance inward from its seaward margin. The hard-rocky floor of this bank is covered with a layer of flocculent calcareous mud which when the water is agitated becomes churned into a milky mass fatal to coral growth Thus coral heads can very rarely attain a foothold excepting near the seaward edges of the bank where pure ocean water in large measure replaces the silt laden waters of the bank.

In other words, the coral patches which rim the Bahama Bank have merely grown in modern times near the seaward edges of a submerged flat, the extraordinarily level character of which can only be explained by assuming it to have been formed in conformity with sea level. Only a water-level could be so flat.

Daly's (1915, *Proc. Amer. Acad. Arts and Sci.*, Vol. 51, pp. 157–251) opinion that the cooling of tropical seas in glacial epochs had much to do with determining the relative abundance of corals, has opened an interesting field for research, but according to Vaughan (1919, *U. S. National Museum Bulletin* No. 109, p. 256), the West Indian fossil reefs do not support this idea, for corals grew extensively in this region in Pleistocene times.

W. M. Davis, in numerous papers,[1] has called prominent attention to the following well-established facts: That under still-stand conditions, if the land be not surrounded by reefs, the sea will cut into the cliffs faster than the valleys can be excavated by subaërial erosion, and thus the streams will cascade into the sea. Then if the island subsides, or the sea level rises, and drowns the valleys, the submarine slopes at the spur-ends will be steeper than the slopes of the submerged sides of the drowned valleys. Also silt will be largely pocketed at the stream mouths in the inner ends of the drowned valleys, and will settle to the bottom before it reaches the

[1] A good résumé is given in Davis, 1919, *Trans. New Zealand Inst.*, Vol. 51, pp. 6–30.

shores along which corals are growing. I find, for example, that the coarse brown bottom mud of the mid-channel line of Pago Pago Harbor near the inner end of the harbor between Blacklock's Wharf and Pago Pago Stream consists, by weight, of 67 per cent. of volcanic material insoluble in hydrochloric acid and 33 per cent. of calcareous elements composed of shells, *Halimeda,* etc. At mooring buoy "B" about one third the distance from the inner end to the mouth of the harbor the bottom mud is finely divided, brown in color, and 51 per cent. volcanic. At mooring buoy "C," however, which is only 300 meters outward beyond buoy "B," the bottom mud is brown-gray in color and contains only 18.5 per cent. of volcanic elements. While at the mouth of the harbor the mud is a finely divided light gray deposit and contains only 6 per cent. of volcanic material. Thus the bulk of the volcanic silt is deposited on the harbor bottom before it goes more than one-third the distance from the inner end of the harbor to the mouth.

Thus, as Davis shows, coral reefs could form more readily around an emerged or a still-stand shore-line. Davis is the most active defender of Darwin's coral reef theory, yet the sequence of fringing reefs being converted into barrier reefs through subsidence of the land or by rise of sea level, and finally the conversion of these barrier reefs into atoll rims has not been proven even in a single instance, although it is the crux of Darwin's theory. As Davis admits we have not been able to read the history of the atolls, for there is no central island whose shore line can be interpreted.

There is on the contrary evidence that barrier reefs have in many places arisen as barriers along the seaward edges of submerged plateaus and remained such throughout their history, or have fused in places with fringing reefs which grew contemporaneously outward from the shores. Thus we have Vaughan's evidence that the old elevated reef of Florida which now constitutes the islands from Soldier's Key to the southern end of Big Pine Key is not a mere elevated part of the limestone platform upon which it grew for the platform is of oölitic formation and contains very few corals.

As has been pointed out by Daly, Darwin's theory does not explain the nearly uniform depth of about 20 fathoms, and the remarkably flat floors, of the bottoms of Pacific lagoons; whereas such facts are readily understood if we suppose the ocean level to have risen about 20 fathoms since glacial times. An obstacle to the general acceptance of Daly's theory lies, however, in the fact that if these level-bottomed submerged banks were formed at a time of lowered ocean level caused by the withdrawal of water from the seas to form the polar ice-caps, then the submarine banks of the tropical Pacific should be submerged to the same depth as those of the tropical Atlantic, but over the Bahama Banks we find an area of 27,000 square miles with depths only varying from 2 to 5 fathoms, instead of 15 to 20 fathoms as in the Pacific atoll lagoons.

On the other hand, the remarkably uniform and relatively narrow width of considerably less than a mile shown by the atoll rims of the Paumotos, Ellis, Gilbert, and Marshall Islands suggests that these atoll groups are all of about one and the same age, and as we now know the growth-rate of Pacific corals to be almost twice as rapid as that of corresponding genera in the Atlantic it would seem that these atolls could have attained their present stage by growth commenced after the close of the last glacial epoch. The living coral reefs of the Pacific are probably less than 40,000 years old, and this is strongly suggestive of the validity of Daly's theory in so far as it applies to the modern reefs of the Pacific. The growth-rate of Samoan corals is rapid, massive *Porites* heads growing upward about 18 mm., branched *Porites* 30 mm., *Pocillopora* 38 mm., and *Acropora* 55 mm., per annum. Thus a reef of massive *Porites* might grow upward 100 feet in 1,600 years. It will be recalled that Stanley Gardiner estimated that in the Maldives a coral reef might become 100 feet thick in 1,150 years; and thus our independent estimates are of the same order of magnitude.

Making use of diving apparatus, I have studied the reefs at depths of 2 to 6 fathoms, and find that when corals die which grew in depths below the influence of the breakers, they commonly remain in place and soon became coated with layers of lithothamnion, and are thus not only preserved as elements of the reef but the stony mass actually increases in volume, the lithothamnion cementing all dead elements of the reef into a more or less compact framework into the interstices of which sand and other fragments soon settle.

It seems probable that the reefs now living in the Pacific are structures which have originated in modern times upon submerged slopes and platforms of marine erosion. Being not more than 40,000 years old, these reefs have not existed long enough to have been subjected, except in rare instances, to appreciable subsidence or elevation of the land masses upon which they have attained a foothold.

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